A Simulation Study of Emergency Vehicle Prioritization in Intelligent Transportation Systems

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***Abstract*—Emergency vehicle prioritization is important to the efficiency of emergency services. To address certain challenges in emergency vehicle prioritization, we perform microscopic simulations of an intelligent transportation system, where emergency vehicles broadcast certain information about their routes to nearby vehicles and traffic lights. Our study shows that broadcasting the route information can help reduce the response time of emergency vehicles significantly. In certain case, travel time of emergency vehicles can be as low as 37.1% of that of non-priority vehicles.**

I. Introduction

As response time of *Emergency Vehicles (EmVs)* is critical to the effective delivery of emergency services [1], EmVs are given a high priority to use roads. Prioritization of emergency vehicles is commonly achieved in two ways. One of them is the implementation of move over laws that ask non-priority vehicles to give way to EmVs. Another is traffic light pre-emption, which temporarily manipulates traffic lights at the intersections on the path of EmVs such that conflicting traffic can be blocked. There are several challenges to the existing prioritization methods. First, a driver may not be able to see an incoming EmV and hear the EmV's siren in certain situations. Second, a driver may misjudge the distance to an EmV. Third, traffic light pre-emption does not work for intersections without traffic lights.

With the development of vehicular communication technologies, we envisage an *Intelligent Transportation System (ITS)* that addresses the aforementioned challenges. In the system, an EmV periodically broadcasts certain information using *Dedicated Short-Range Communications (DSRC)* [2]. The information describes the lane being used by the EmV and the road segments that the EmV is going to pass within a certain distance, called *clearance distance*. Since the information is delivered through a wireless channel, the detection of incoming EmVs can be more effective than relying on drivers' visual and auditory detection. Impact of human misjudgement can be minimized as processors on vehicles make automatic measurements of the situation. In addition, intersections can be pre-empted even if there is no traffic light.

We perform a microscopic simulation study to evaluate the effectiveness of the proposed system using our microscopic traffic simulator, *SMARTS* [3]. The traffic simulator is capable of simulating traffic of any road network across the world based on OpenStreetMap data [4]. Vehicles and traffic lights are individually modelled. Movement of vehicles is based on a car-following model and a lane-changing model. Timing of traffic lights can be dynamically adjusted based on incoming traffic at intersections. There can be multiple types of vehicles. Personal driving characteristics are also simulated. For example, EmVs tend to show an aggressive driving behaviour. Figure 1 shows an example simulation running in SMARTS. The simulation includes $15,000$ vehicles in Midtown Manhattan.

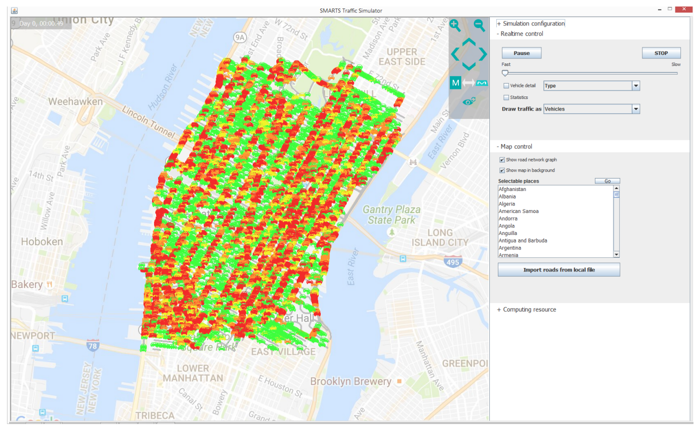


Fig. 1: Simulation of traffic in Midtown Manhattan using the SMARTS simulator. Vehicles are shown as coloured icons. Green vehicles are moving fast and red vehicles are moving slowly.

Our simulations show that the proposed ITS can effectively prioritize EmVs in complex road networks even with high traffic loads. EmVs arrive their destinations significantly faster than non-priority vehicles. For example, the average travel time of EmVs can be 7.3 minutes less than that of non-priority vehicles in Midtown Manhattan with $15,000$ vehicles. Our experiments show the impact of a range of factors, including road network location, move over rule, traffic volume, clearance distance of EmV and travel distance.

The rest of the paper is organized as follows. Section II shows the related work. The proposed ITS is detailed in Section III. Experimental results are shown in Section IV. We conclude the paper in Section V.

II. Related Work

A large body of work has been focused on the prioritization of EmVs. For example, a research on emergency vehicle manoeuvres [5] shows the improvement of response time based on certain lane-changing strategies. Different to our work, the research does not consider traffic light pre-emption as it is focused on highway systems. Chen et al. developed an approach that can optimize an EmV's route plan based on the current and historical traffic information [6]. Differently, we assume that an EmV uses the shortest path to reach their destinations as it is normally the optimal path if roads can be pre-empted. A recent research shows the improvements of response time in a real ITS [7]. The system requires a control centre, which predicts the routes of EmVs and pre-empts traffic lights on the predicted routes. In case that an predicted route is different to the actual path taken by EmV, the control centre cancels the existing pre-emption and re-predicts the route. Different to this approach, our proposed system does not require a control centre as non-priority vehicles and traffic lights can detect EmVs based on short range communications.

Research on EmV prioritization must use microscopic traffic simulations to evaluate the proposed approaches. Microscopic simulations provide the most realistic simulations as they model vehicles and traffic lights individually. Prominent microscopic traffic simulators include SUMO [8], CORSIM [9], TRANSIMS [10] and VISSIM [11]. SMARTS has an advantage over many microscopic traffic simulators as it can exploit distributed computing resources for high performance simulations. This capability enables the simulator to perform faster-than-real-time simulations with large-scale road networks, which is useful for city-wide traffic predictions. Our simulator also has a better cross-platform capability as it is developed in Java.

A recent research uses SUMO to experiment traffic light pre-emption [12]. Compared to this research, our study evaluates the changes of response time based on a wider range of factors. Zhang et al. evaluate the impact on EmVs by extending the CORSIM simulator [13]. Their work assumes that drivers can become aware of EmVs depending on their distance to the EmVs. It does not consider the situations where people cannot see the EmVs or hear their sirens. Differently, another research proposes EmV prioritization based on vehicle-to-vehicle communications [14]. The approach requires EmVs to broadcast their position and velocity. Similar to this approach, we also assume that certain information can be delivered through vehicle-to-vehicle communication. However, we require EmVs to broadcast information about their routes. This helps non-priority vehicles and traffic lights to get a more accurate cognition of the situation.

III. Emergency Vehicle Prioritization

In the proposed ITS, an EmV periodically broadcasts DSRC messages. A message contains two pieces of information about the EmV. The first is the route information of the EmV, which includes its current road segment and other road segments on its path ahead. We only consider road segments within the clearance distance, which can vary based on specific scenarios. The second piece of information shows the current lane of the EmV. Based on the two pieces of information, non-priority vehicles can know whether they are impeding an EmV. If the clearance distance is larger than the communication range of DSRC, we assume that vehicles, traffic lights and other Roadside Units (RSUs) can relay a message to all vehicles and traffic lights with the clearance distance. We also assume that all vehicles are equipped with GPS so that they are aware of their own location at all times.

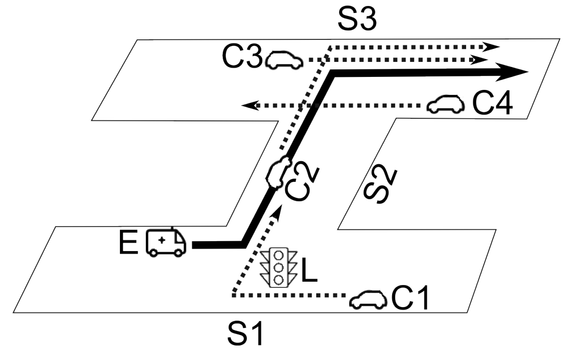


Fig. 2: An example scenario of EmV prioritization. The route of an emergency vehicle E passes Street S1, S2 and S3. There are four non-priority vehicles (C1, C2, C3 and C4) and one traffic light L. Travel directions of vehicles are also shown.

When the message from an EmV reaches an intersection with traffic lights, a processing unit at the intersection checks whether the EmV's route crosses the intersection. If this is true, the lights at the intersection will be adjusted such that the street on the EmV's path will get green light as soon as possible. If the message reaches multiple intersections on the EmV's path, lights at all the intersections will be pre-empted for the EmV. When the message reaches a non-priority vehicle, the vehicle needs to give way to the EmV under two circumstances. First, if the non-priority vehicle is in the EmV's current road segment or is in a road segment that will be used by the EmV, the vehicle may need to change lane as required by the local move over law. The vehicle may also needs to stop based on the law. Second, if the vehicle is approaching an intersection on the EmV's path from a direction that will conflict with the EmV's travel direction, the vehicle needs to stop at the intersection until the EmV passes.

An example scenario is shown in Figure 2. We assume that all the non-priority vehicles and the traffic light are within the clearance distance from the emergency vehicle E. The following events will happen after E broadcasts its route, which is shown as the solid line with arrow. Traffic light L allows E to turn to Street S2 and blocks non-priority vehicle C1, which is going to turn to the same street. C2 changes lanes if it is in the same lane of E. C2 may also stop based on the local traffic law. Although there is no traffic light at the intersection between Street S2 and Street S3, non-priority vehicles travelling on S3 still give way to E as they know that E is going to turn to S3. Therefore, C3 and C4 stop at the intersection until E passes.

IV. Experiments

We evaluate the travel time of EmVs in the proposed ITS using our SMARTS simulator. We define *travel time ratio*, R, as follows.

$$R = \frac{T_{wo}}{T_w}$$

T_{wo} is the benchmark travel time collected from a simulated environment *without* background traffic and traffic lights. In other words, it is the shortest possible travel time of EmVs. Differently, T_w is collected when the roads are filled with random background traffic. Traffic lights are also enabled for collecting T_w. As travel time ratio is always between 0 and 1, it gives a normalized measurement of travel time.

Experiments are set up based on five parameters: road network location, move over rule, traffic volume, clearance distance of EmV and travel distance.

- **Road Network Location** Simulation areas are chosen from three different locations. One is the downtown area of Melbourne, Australia. One is Midtown Manhattan in New York. The third area is a part of the central London. The road network structures are vastly different between the three areas. We assume that all the roads have two lanes.
- **Move Over Rule** There exist many variants of move over rule around the world. We perform simulations with three variants. The first variant is used in Australia [15]. It requires non-priority vehicles move away from the passing lane when EmVs are approaching from behind. We label this rule as *MA*. In the second variant, non-priority vehicles not only need to move away from the passing lane but also need to pull off. This rule is used in some countries, such as Canada [16]. We label this rule as *PO*. The third variant gives flexible use of traffic lanes to non-priority vehicles as they can use any lane not occupied by EmVs. Certain countries, e.g., Norway [17], use this variant. This rule is labelled as *FLEX*. For each road network, we first compare travel time ratios of EmVs with the three variants. The variant with the highest travel time ratio is used in the remaining tests with the road network. Based on our results, PO is the best variant for all the road networks.
- **Traffic Volume** Volume of background traffic has a significant impact on EmVs' response time. The volume is set to 0 for collecting the benchmark travel time, T_{wo}. The volume is set to a certain positive value for collecting T_w. When testing the impact of move over rule, clearance distance and travel distance, the volume is set to a default value such that the average traffic speed matches the real statistics [18], [19], [20].
- **Clearance Distance of EmVs** EmVs that ask for clearance in a longer distance may have a higher chance to reach their destinations without slowing down. We evaluate the impact of clearance distance on travel time.
- **Travel Distance** A vehicle that travels a longer distance may be impeded by more vehicles and red lights, which can potentially lead to a lower travel time ratio. We evaluate the impact of this factor as well.

TABLE I: Experiment settings for Melbourne (MEL), Manhattan (MAN) and London (LND). Each line details one set of experiments.

Move Over Rule for EmVs	Traffic Volume	Clearance Distance of EmVs	Travel Distance
MA, PO, $FLEX$	$5k$ (MEL) $15k$ (MAN, LND)	$150m$	$3km$
PO	$3k-7k$ (MEL) $5k-25k$ (MAN, LND)	$150m$	$3km$
PO	$5k$ (MEL) $15k$ (MAN, LND)	$50m-250m$	$3km$
PO	$5k$ (MEL) $15k$ (MAN, LND)	$150m$	$1km-5km$

Table I shows the experiment settings. We run experiments with three road networks. In each experiment, we create 50 random routes using Dijkstra's shortest path algorithm [21]. We assign the routes to 50 EmVs and collect the benchmark travel time, T_{wo}, without adding background traffic and traffic lights. We then run the same simulation with background traffic and traffic lights. The travel time ratio of each EmV, T_w, is then computed. Finally, the average and deviation of T_{wo} and T_w are reported. When experimenting traffic volume and travel distance, we also run additional simulations, where we use non-priority vehicles to replace the EmVs. Those non-priority vehicles use the same routes as the EmVs. By doing this, we can compare the travel time ratio between non-priority vehicles and EmVs.

A. Results

1) Melbourne: The results are shown in Figure 3. Figure 3a shows that the move over rule, *PO*, achieves the highest travel time ratio at 92.1%. Figure 3b shows that EmVs' average travel time ratio drops slowly from 94.9% to 86.8% when the background traffic increases from 3000 vehicles to 7000 vehicles. The lowest ratio is still high due to the pre-emption of roads. The time ratio of normal vehicles (non-priority vehicles) is significantly lower than EmVs' records. When there are 7000 background random vehicles, non-priority vehicles need almost double the optimal time to reach their destination as the travel time ratio is only 52%. EmVs' records also show a smaller deviation than that of normal vehicles. The impact of clearance distance on EmVs' response time is minimal when the distance is greater than 50 metres. When the clearance distance is 50 metres, the travel time ratio is slightly lower at 88.9%. Figure 3d shows that EmVs maintain a high travel time ratio between 90.5% and 92.9% with different travel distances. Non-priority vehicles, on the other hand, can only achieve a ratio between 52.8% and 64.4%. Our raw data shows that EmVs' average travel time is 7 minutes when their travel

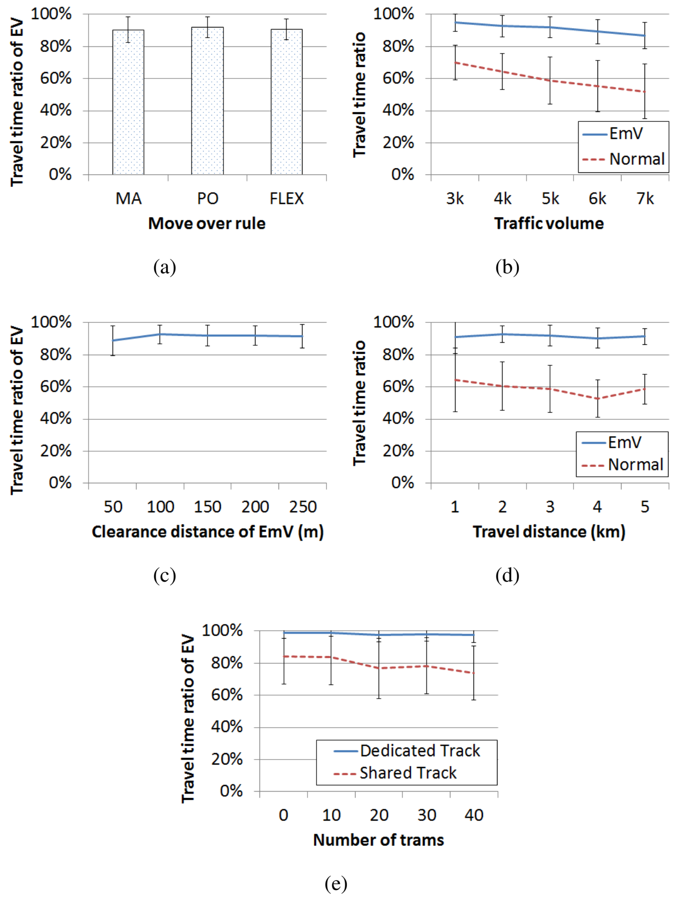


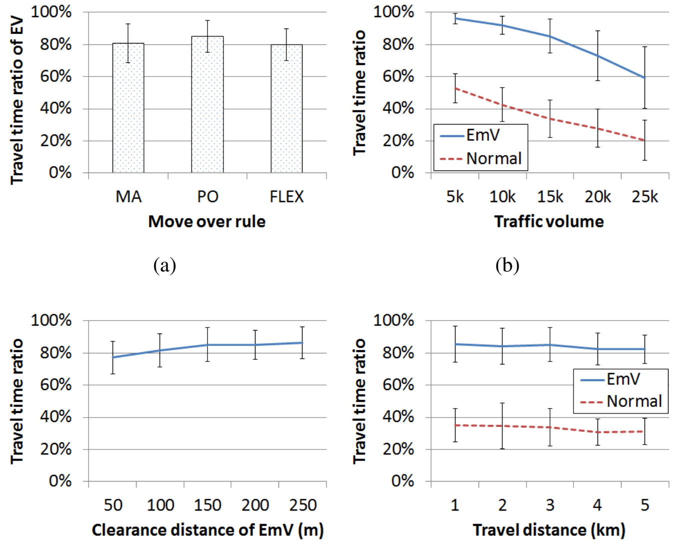
Fig. 3: Results for Melbourne road network.

distance is $5km$. The travel time is still lower than the real average response time collected from the area between 2015 and 2016, which is 10 minutes [22].

We also perform an interesting experiment related to the impact of trams on EmVs' travel time. Melbourne has a large scale tram network. Tram tracks are either dedicated to tram use or shared by all types of vehicles. In the previous case, tram tracks are empty during most of the day. If EmVs use these tracks, they are less likely to be blocked by other vehicles. On the contrary, shared tram tracks normally have a more negative impact on EmVs' response time. This is not only because there are more vehicles travelling on the tracks, but also because non-priority vehicles must give way to trams at tram stops due to local regulation. In this experiment, we compare the travel time of EmVs in both scenarios. As tram tracks are concentrated in Melbourne CBD, we use a road network that only covers the CBD area for this experiment. The travel distance of EmVs is set to $2.5km$. We fill the network with 1800 normal vehicles such that the average travel speed matches the real statistics [18]. We vary the number of trams between 0 and 40. Traffic lights are not included in this experiment. The results are averaged from 50 EmVs with random source and destination. Figure 3e shows that EmVs' travel time nearly reaches the optimal time if they use dedicated tram tracks where possible. There is only a minor drop of response time ratio (98.9% to 97.5%) when the number of trams increases from 0 to 40 as EmVs are blocked by more trams. The figure also shows that EmVs move significantly slower on shared tram tracks. The response time ratio drops from 84.4% to 74% with the increase of tram volume. This is understandable as EmVs are blocked by more vehicles, which have to give way to trams.

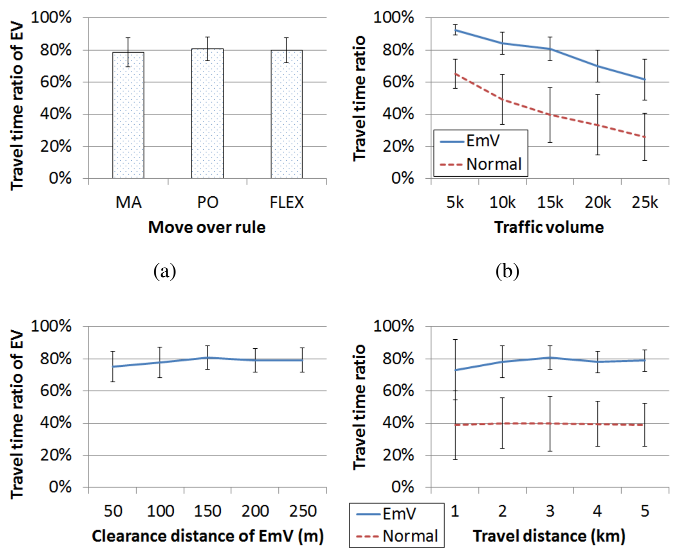
2) *Manhattan:* Results for Midtown Manhattan are shown in Figure 4. Figure 4a shows that PO is still the best rule for EmVs with travel time ratio at 85.2%. The default traffic volume in this area is significantly higher than the setting for Melbourne due to two reasons. First, real statistics show that the average traffic speed in Manhattan is significantly lower than that in Melbourne. Second, the total road length in Midtown Manhattan is higher than that of the Melbourne area. The heavy traffic in Manhattan has a considerable impact on the travel time as expected. Figure 4b shows that the travel time ratio drops from 96.2% to 59.4% when the number of background vehicles increases from 5000 to 25000. Non-priority vehicles perform significantly worse as their highest travel time ratio is only 52.7% when there are 5000 background vehicles. The impact of clearance distance is more obvious in Manhattan than in Melbourne due to the higher level of congestion in Manhattan. Figure 4c shows that EmVs' travel time ratio improves from 77.2% to 86.4% as clearance distance is increased from 50 metres to 250 metres. Finally, we observe a slight drop of travel time ratio in vehicles with the increase of travel distance. EmVs are constantly better than normal vehicles by a significant margin when travel distance changes. The travel time ratio of EmVs drops from 85.5% to 82.3% while that of normal vehicles drops from 35.1% to 31.3%. When all parameters are at the default values, the average travel time of non-priority vehicles is 11.6 minutes while that of EmVs is 4.3 minutes, which is 7.3 minutes less. This means that EmVs' travel time is only 37.1% of that of non-priority vehicles under the default settings.

3) *London:* The results are shown in Figure 5. Similar to the results from other tests, we observe that PO is the best move over rule. The travel time ratio is 80.8% for PO. The impact of traffic volume is similar to that for Manhattan area. EmVs' advantage over non-priority vehicles is between 27.3% and 41.1% in terms of the travel time ratio. There is an improvement of EmVs' travel time ratio (75.1% to 80.8%) as clearance distance is increased from 50 metres to 150 metres. The ratio does not change significantly when clearance distance is increased over 150 metres. Figure 5d shows that EmVs' average response time gets an improvement when travel distance is increased from $1km$ to $2km$. This is understandable as randomness of traffic conditions across the road network has a significant impact on short routes as evidenced by the large deviation of travel time ratios at $1km$.



(a) (b) (c) (d)

Fig. 4: Results for Manhattan road network.



(a) (b) (c) (d)

Fig. 5: Results for London road network.

V. Conclusion

Our study with microscopic simulations shows that the response time of emergency vehicles in an ITS can be close to the optimal travel time if roads can be pre-empted for certain distance ahead. Prioritized emergency vehicles can reach their destinations significantly faster than non-priority vehicles.

Acknowledgment

This research was supported by a Discovery Project grant DP130103705 and a Linkage Project grant LP120200130.

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